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Development of long coated conductors with high in-field I_c performance by PLD method at high production rate

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Abstract

We fabricated short samples and a 93 m long coated conductor (C. C.) of $EuBa_2Cu_3O_{7-\delta}$ (EuBCO) with $BaHfO_3$ (BHO) by the IBAD and the PLD methods, which exhibited the high in-field minimum I_c value, (I_c(min)), performance of 141.2 (77 K in 3 T) and 411.3 (65 K in 3 T) A/cm-w for a short sample, and 133.9 (77 K in 3 T) A/cm-w for 93 m long C. C. with 3.6 µm in thickness, respectively. Moreover, this long EuBCO with BHO coated conductor also showed high uniform longitudinal I_c distributions and *n*-value in magnetic fields. However, the deposition rate for obtaining the high in-field I_c performance was comparatively slow down to 10 µm/h. To realize the low production cost for EuBCO with BHO coated conductors, improvement of the deposition rate of the EuBCO with BHO layer with high I_c is required. To solve this problem, we optimized growth conditions including deposition conditions. One of the objectives of this work was changing the layer growth mode from the vapor-solid (VS) mode to the vapor-liquid-solid (VLS) one to fabricate EuBCO with BHO layers for achievement of high production rate and maintaining the high in-field I_c and J_c performance of the films deposited at slow deposition rates. As a result, we fabricated EuBCO with BHO coated conductors at a high deposition rate of about 40 µm/h and production rate of about 10 m/h, which revealed the I_c(min) value of 48.7 A/cm-w at 77 K in 3 T for 1.35 µm in thickness.

Keywords: EuBCO with BHO coated conductors; IBAD and PLD method; VLS; high depositon rate

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Introduction

$REBa_2Cu_3O_{7-\delta}$ (REBCO, RE: rare earth element) with $BaMO_3$ (BMO, M: metal) coated conductors [1, 2] have been expected for the industrial and commercial applications at high temperatures in magnetic fields, such as magnetic resonance imaging (MRI) and heavy ion medical accelerator etc. Recently, we have found that $EuBa_2Cu_3O_{7-\delta}$ (EuBCO) with $BaHfO_3$ (BHO) coated conductors by IBAD and PLD methods show higher critical current densities (J_c) and critical currents (I_c) at high temperatures in self and magnetic fields than those of $YBa_2Cu_3O_{7-\delta}$ (YBCO) and $GdBa_2Cu_3O_{7-\delta}$ (GdBCO) coated conductors [3]. The experimental results of REBCO bulk materials and our REBCO coated conductors indicate that EuBCO has higher critical temperature (T_c), J_c, I_c and growth rate as well as uniformity of those properties for long length conductors than those of YBCO and GdBCO at high temperatures in self and magnetic fields. We fabricated short samples of EuBCO with BHO and a 93 m long EuBCO with BHO coated conductor. The obtained I_c(min) values in the all angles of applied magnetic field of 3 T for respective short specimen and the long (93 m) conductor are 141.2 and 133.9 A/cm-w. EuBCO with BHO for the both conductors were about 3.6 μm in thickness [3]. On the other hand, the characteristics of uniformity of I_c distributions for long length EuBCO with BHO coated conductors and the I_c-B-θ performance at low temperature and high magnetic fields, for example, 65 K in 3 T for MRI and 35 K in 10 T for the medical accelerator of EuBCO with BHO coated conductors have not been yet evaluated. In addition, to realize low technical cost of EuBCO with BHO coated conductors for industrial and commercial applications, the much higher deposition rate is required.

1. Experimentals

The EuBCO with BHO were deposited by a PLD method on 10 mm wide CeO_2 / $LaMnO_3$ / IBAD-MgO / Y_2O_3 / $Gd_2Zr_2O_7$ / Hatelloy^{TM} C-276 substrates. The value of in-plane and out-of-plane texturing degrees (Δϕ and Δω) of the CeO_2 cap layer were about 1～ 3 and 1 ～ 2 degrees, respectively. A 200 W industrial XeCl excimer laser with a wavelength of 308 nm was used at a pulse repetition rate of 177 Hz and a pulse energy of about 600 mJ, which lead the deposition rate of about 40 μm/h (high deposition rate) for an EuBCO with BHO layer. On the other hand, A 80 W KrF excimer laser with a wave length of 248 nm was used at pulse repetition rate of 150 Hz and a pulse energy of about 330 mJ, which lead the deposition rate of about 10 μm/h (low deposition rate) for an EuBCO with BHO layer. The optical system is synchronized to the laser pulse and scanning of the laser beam to on an EuBCO with BHO bulk target was controlled as well. The laser repetition rate at 177 Hz is divided into 4 plumes which are almost the same in size and shape. Commercially available targets of sintered $EuBa_2Cu_3O_X$ or off-stoichiometric $EuBaCu_{3.2}O_X$ containing 3.5 mol% doped BHO with a diameter of 6 inch were used for deposition of the EuBCO layers with BHO nano-rods. The deposition temperature was over 900 °C for a substrate tape with a transferring speed of 30 m/h. The oxygen pressure was maintained to be at about 600 mTorr with a flow of 10 sccm oxygen. The T-S distance (distance between the target and the substrate) was set about 100 mm. The thickness of the EuBCO layer containing BHO nano-rods was 450 to 500 nm for one time deposition with the substrate tape transferring speed of 30 m/h as a typical value.

2. Results and discussions

Figures 1 (a) and (b) show the angular dependence of the applied magnetic field of 3 T on the I_c values for EuBCO with BHO coated conductor with low deposition rate at 77 K and 65 K. The EuBCO with BHO layer was about 3.6 μm in thickness. The EuBCO with BHO coated conductor shows high I_c(min) values of 141.2 A/cm-w and 411.3 A/cm-w in 3 T at 77 K and 65 K, respectively. However, I_c isotropy of EuBCO with BHO coated conductors deteriorated at 65 K in 3 T.

Figure 2 (a)～(d) indicate the longitudinal (a) I_c distribution at 77 K in self-filed, (b) *n*-value at 77 K in self-field, (c) I_c distribution at 77 K in 0.3 T and (d) *n*-value at 77 K in 0.3 T of the 93 m long EuBCO with BHO coated conductor at low deposition rate. A 93 m long EuBCO with BHO coated conductor has uniform longitudinal I_c distributions of 4.07 % of standard deviation (STDEV) at 77 K in self-field and 5.26 % of STDEV at 77 K in 0.3 T, respectively. However, the uniformity of STDEV at 77 K in 0.3 T slightly deteriorated. It is thought that this is due to the BHO nano-rods distributions of long length EuBCO layers. On the other hand, the STDEV of *n*-value at 77 K in 0.3 T was improved in comparison with that at 77 K in self-field. It is considered that the influence of intra-current which flows in the grain became dominant due to reduction of the influence of weak-link which limit the inter-current between grains.

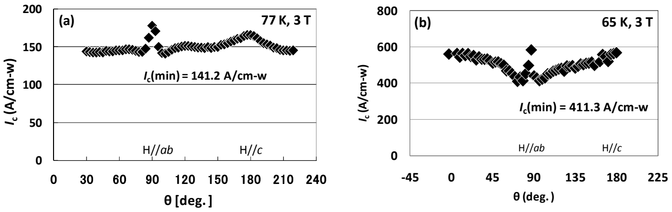

Fig. 1 Angular dependence of applied magnetic field of 3 T on I_c values for EuBCO with BHO coated conductor at (a) 77 K and (b) 65 K.

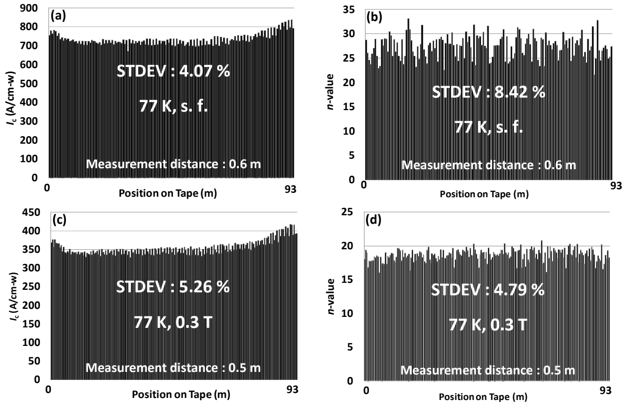

Fig. 2 (a) I_c distribution at 77 K in self-filed, (b) *n*-value at 77 K in self-field, (c) I_c distribution at 77 K in 0.3 T and (d) *n*-value at 77 K in 0.3 T of a 93 m long EuBCO with BHO coated conductor.

Figure 3 (a) shows a SEM image of the surface of high I_c EuBCO with BHO coated conductor and (b) a cross-sectional high-angle annular dark field (HAADF) image of high I_c EuBCO with BHO coated conductor at low deposition rate. From these figures, we found out that liquid phase exists in the surface of high I_c EuBCO with BHO coated conductor. This suggest that changing the EuBCO layer growth mode from the vapor-solid (VS) mode to the vapor-liquid-solid (VLS) one might be important for fabrication at high deposition rate with high I_c, because I_c values of REBCO with BMO coated conductors by high deposition rate shows lower than those of REBCO with BMO coated conductors by low deposition rate [4].

Based on this result, we optimized growth conditions including deposition temperature, O_2 pressure, composition of EuBCO with BHO target and T-S distance etc. to change the growth mode from VS mode to the VLS one for achieving high deposition rate. In particular, the set deposition temperature was changed to 1145 from 1095 °C. The composition of EuBCO with BHO target was changed to $EuBa_2Cu_{3.2}O_X$ + BHO from $EuBa_2Cu_3O_X$ + BHO.

Figure 4 shows the thickness dependence of EuBCO with BHO coated conductor on I_c values at 77 K in 3 T for different deposition conditions: (a) low deposition rate with the VLS growth mode and high deposition rate with the VS growth mode and (b) low deposition rate with the VLS growth mode and high deposition rate with the VLS growth mode. The deposition rate of VLS and VS growth mode for EuBCO with BHO layer by high deposition rate were almost same rate of about 40 μm/h. To realize the VLS growth mode for EuBCO with BHO layer at high deposition rate, we optimized deposition conditions, especially deposition temperature and composition of EuBCO with BHO target. Form the results of Fig. 4, the I_c(min) values of the EuBCO with BHO at 77 K in 3 T by high deposition rates as well as those of EuBCO with BHO by low deposition rates were increased linearly with increasing the thickness of the EuBCO with BHO layer. It is considered that J_c of EuBCO with BHO layer at high deposition rate increased because the crystallinity and connectivity of EuBCO grains were improved by the VLS growth mode, for example, Δϕ and Δω of EuBCO with BHO layer were improved from 3.16 ° to 2.21 ° and 0.98 °

to 0.80 ° by VLS growth mode, respectively. As a result, we successfully fabricated EuBCO with BHO coated conductors at a high deposition rate of about 40 μm/h and production rate of about 10 m/h, which revealed the I_c(min) value of 48.7 A/cm-w at 77 K in 3 T for 1.35 μm in thickness.

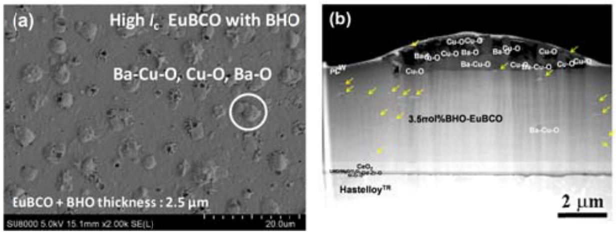

Fig. 3 (a) SEM image of high I_c EuBCO with BHO surface and (b) cross-sectional HAADF images of high I_c EuBCO with BHO at low deposition rate. The liquid phase exists in the high I_c EuBCO with BHO surface.

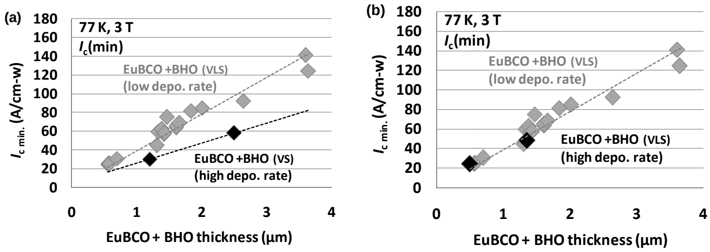

Fig. 4 Thickness dependence of EuBCO with BHO on I_c values at 77 K in 3 T for different deposition conditions: (a) low deposition rate with VLS growth mode and high deposition rate with VS growth mode and (b) low deposition rate with VLS growth mode and high deposition rate with VLS growth mode.

3. Conclusion

We evaluated the I_c-B-θ profile at 65 K in 3 T, the longitudinal distributions of I_c and n-value of EuBCO with BHO coated conductors. As a result, an EuBCO with BHO coated conductors with 3.6 μm in thickness revealed high I_c(min) value of 411.3 A/cm-w at 65 K in 3 T and uniform longitudinal I_c distributions and n-value in magnetic fields. Moreover, to realize low technical cost of EuBCO with BHO coated conductors for industrial and commercial applications, we optimized growth conditions by which the layer growth mode have changed from the vapor-solid (VS) mode to the vapor-liquid-solid (VLS) one in order to fabricate EuBCO with BHO coated conductors at high production rate and maintaining the high in-field I_c performance. As a result, we successfully fabricated EuBCO with BHO coated conductors at a high deposition rate of about 40 μm/h and production rate of about 10 m/h, which revealed the I_c(min) value of 48.7 A/cm-w at 77 K in 3 T for 1.35 μm in thickness.

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